

Advanced Diagnostic Characterization of High-Power Hall Thruster Wear and Operation

AIAA-2012-4036

George J. Williams, Jr.

The Ohio Aerospace Institute
NASA Glenn Research Center
Cleveland, OH 44135

George C. Soulas and Hani Kamhawi

NASA Glenn Research Center
Cleveland, OH 44135

**48th AIAA Joint Propulsion Conference
July 31, 2012**

Scope and Outline

Preliminary Optical Emission Spectroscopy (OES) data and analysis

- **Correlation of B I OES signal with thruster operating condition provides a low-cost method of real-time evaluation of Hall thruster insulator erosion**
- **Plasma OES signals provide support for intrusive and numerical investigations of plasma parameters**

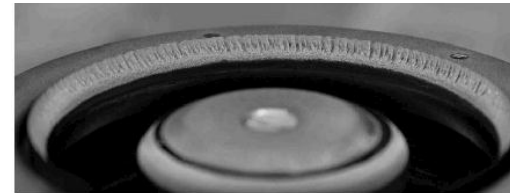
Outline

- **Context and Motivation**
- **Method**
- **Preliminary demonstration**
- **Overview of B-OES trends**
 - **HiVHAc EM (EDU1)**
 - **NASA 300M**
 - **NASA 457Mv2**
 - **Discussion**
- **Plasma Measurements**
- **Summary and Conclusions**

Context and Motivation

Thruster service life remains a mission constraining aspect of all electric propulsion devices including Hall thrusters

- **Extensive investigation and characterization of low-power HETs**
 - **SPT-100 and its derivatives have been repeatedly characterized showing a primary dependence of wear on discharge voltage**
 - **BHP-4000 qualified by Aerojet >10,400 hr, each segment at a different operating condition, 300-400 V**
 - **NASA-77M used in two 300 hr wear tests,**
 - **NASA-103M.XL completed >4700 hr at 700 V**
- **Several design modifications proposed to mitigate or eliminate the service life constraint**
- **Numerical models developed to predict wear**
- **Little or no experimental data to validate wear prediction or mitigation methods for HETs capable of 20+ kW**



900 W HET-LM, Abashkin, IEPC-2007-133



NASA-103M.XL, Kamhawi, AIAA-2010-6860

Context and Motivation

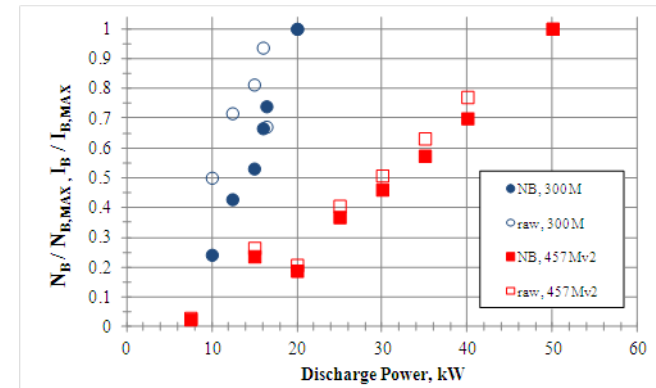
Optical emission spectroscopy is being incorporated into the testing of high-power Hall thrusters to provide

- **A real-time assessment of relative BN insulator erosion rates**
 - Erosion rates are so small that direct measurement is impractical for/during performance testing
 - There is significant discrepancy between predicted and observed plasma structures which increases the uncertainty in service life predictions.
 - **Rapid coupling of wear evaluation with performance testing will provide better mission planning and better performance trades**
- **Data to correlate insulator erosion with thruster operating condition and magnetic field design**
 - Wear tests evaluate the wear at one operating point or integrate over a specific series of operating points
 - Validation of models requires performance and wear characterized at several operating points
 - **Rapid wear evaluation will facilitate model validation and design modifications**
- **A foundation for future non-intrusive diagnostics**
 - **Ultimately eliminate the need for long duration wear tests**

Boron OES Measurement

- **Electron temperature and other excitation mechanisms**
 - **Emission collision cross-sections unknown**
 - **Use an actinometry approximation following Pagnon**
 - **B I (250 nm) transition is to/from the ground state**
 - **Upper state excitation of the Xe II 484 nm transition has similar populating mechanisms as B I 250 nm transition**
 - **Xe I 407 nm transition has an upper state energy level close to Xe I's ionization potential**
 - **Then**

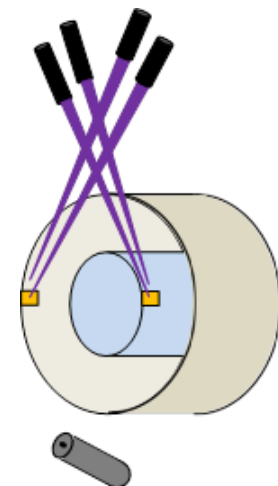
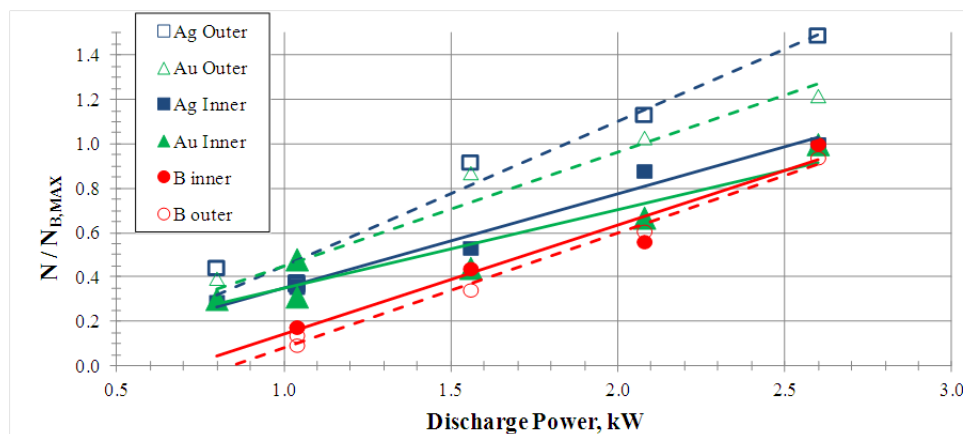
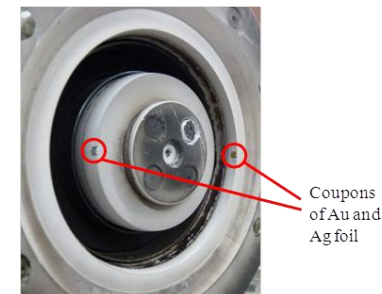
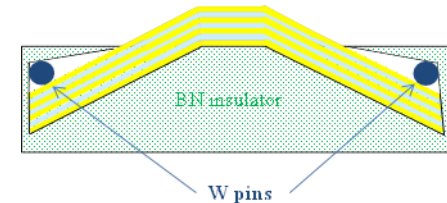
$$N_B \propto \frac{I_{B,250 \text{ nm}} \cdot I_{Xe \text{ I},407 \text{ nm}}}{I_{Xe \text{ II } 484 \text{ nm}}}$$



Pagnon, D., Touzeau, M., and Lasgorceix, P., "Control of the Ceramic Erosion by Optical emission Spectroscopy: Parametric Studies of SPT 100-ML," AIAA Paper2004-3773, July 2004.

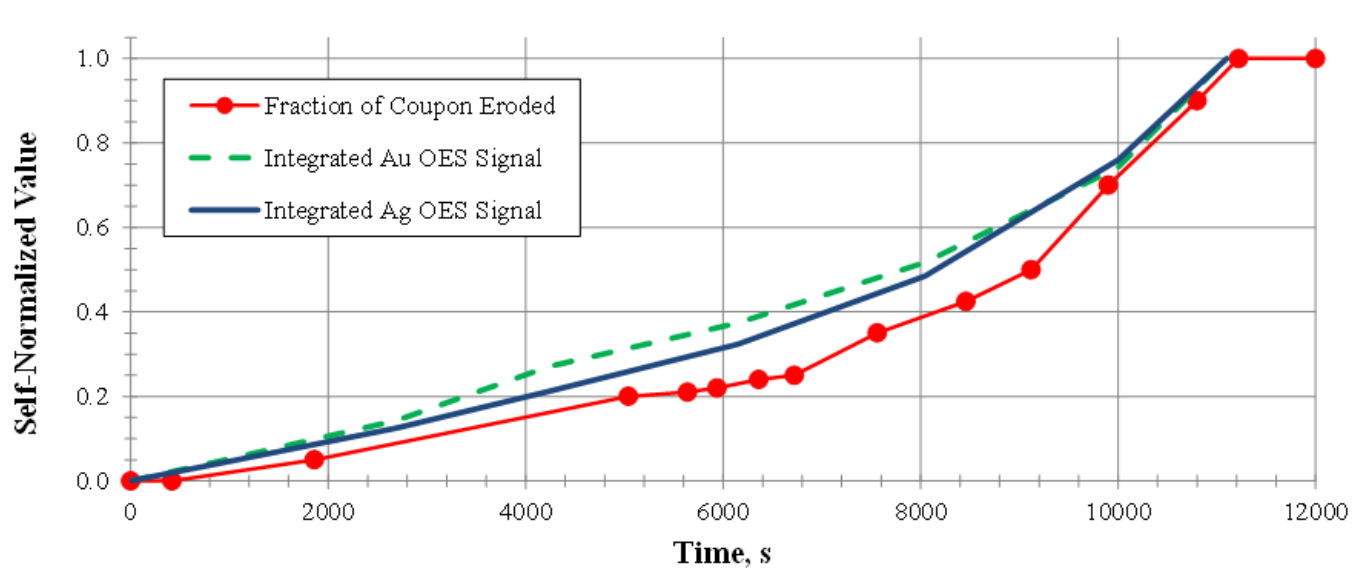
Emission Spectroscopy with Coupons

- Target coupons fabricated to measure real-time erosion rates
 - V-groove hand machined to hold foil
 - 7 alternating layers of 10 μ Au and Ag
- Incorporated into HiVHAc EM thruster
 - One coupon on inner wall, one on outer
 - Operated in VF 8 at GRC over a range of powers
- Optical probes with UV optics and fibers
 - Two focused on coupons
 - Two focused on adjacent BN
- Clear OES from Au, Ag, and B

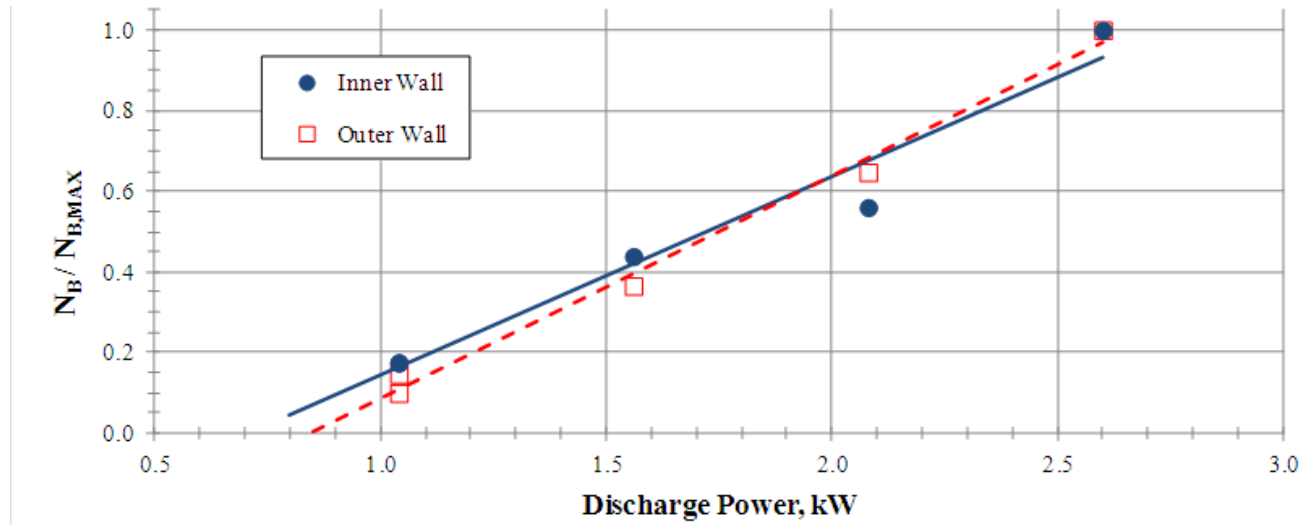


Emission Spectroscopy with Coupons

- Except initially, no distinct transition observed from Au to Ag
 - Size of coupons is too large, erosion is distributed
 - OES signals of Au and Ag trend together
- Coupons eroded from their upstream edge
 - Captured as a function of time by images which allowed a rough estimate of total erosion rate
 - Coupon erosion (disappearance) increased significantly with power
 - Global rate correlates well with integrated emission signals



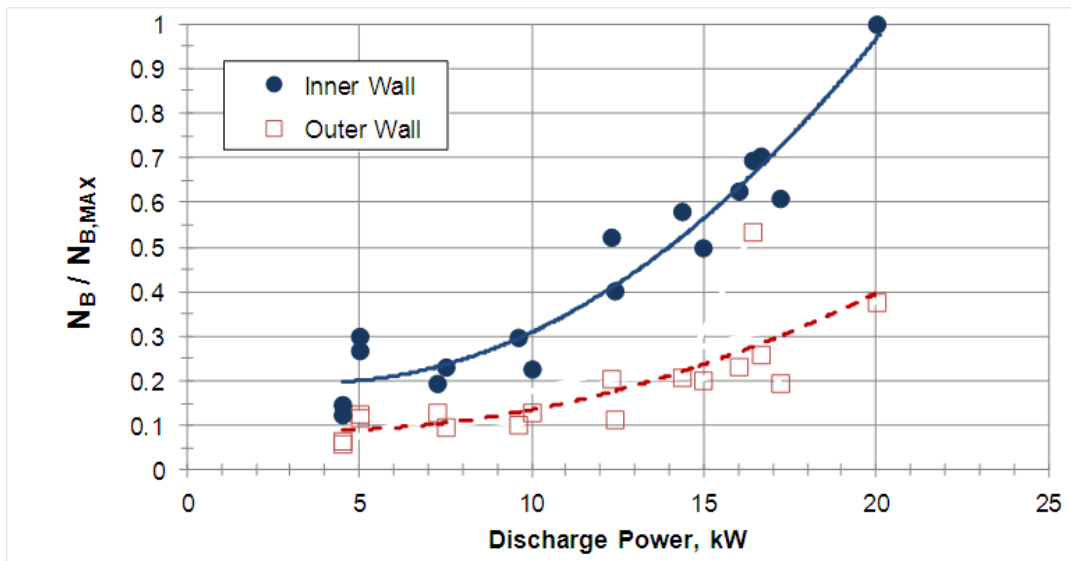
B Emission in the HiVHAc EM



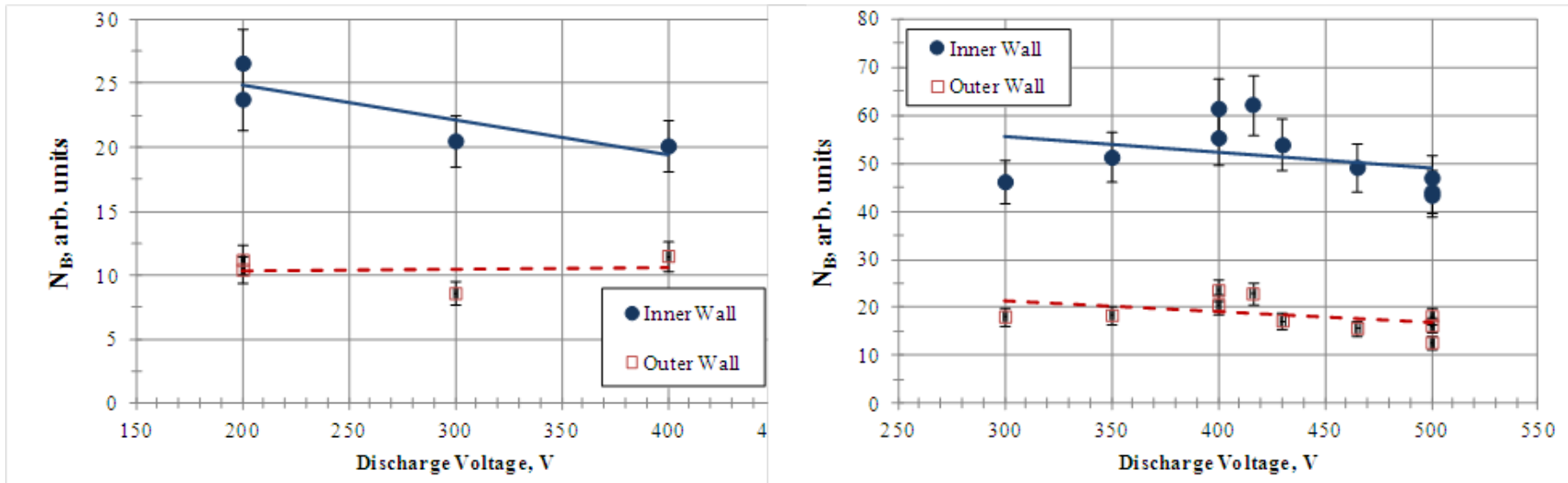
- **N_B varied linearly with power (i.e. voltage, $J_D=5$ A)**
 - HiVHAc EM throttled quickly to accommodate coupon testing
 - Little difference observed between signals from inner and outer walls
- **Trends consistent with expectations**
 - Linear trend with V_D consistent with previous OES tests
 - Validated by weight loss measurements on SPT-derivative thrusters
 - Seen in 1 kW-class thrusters
 - Consistent with previous wear tests
 - Consistent with erosion model predictions and theory

B Emission in the NASA 300M

- Two fiber optic probes collected light from the inner and outer BN walls of the thruster
 - Probes focused a few mm from the exit plane
 - UV-fused silica fibers and optics
- Thruster operated over a range of J_D and V_D
 - N_B increased with power
 - N_B was much greater from the inner wall



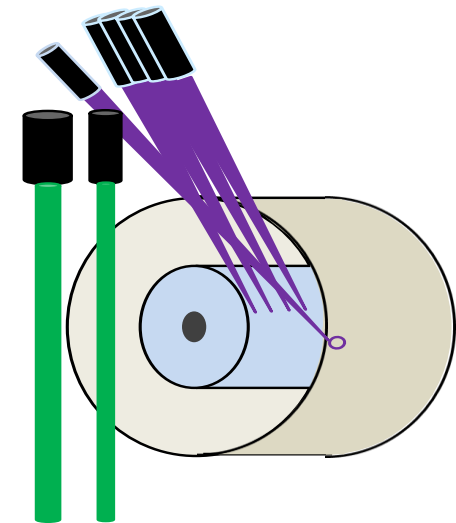
B Emission in the NASA 300M



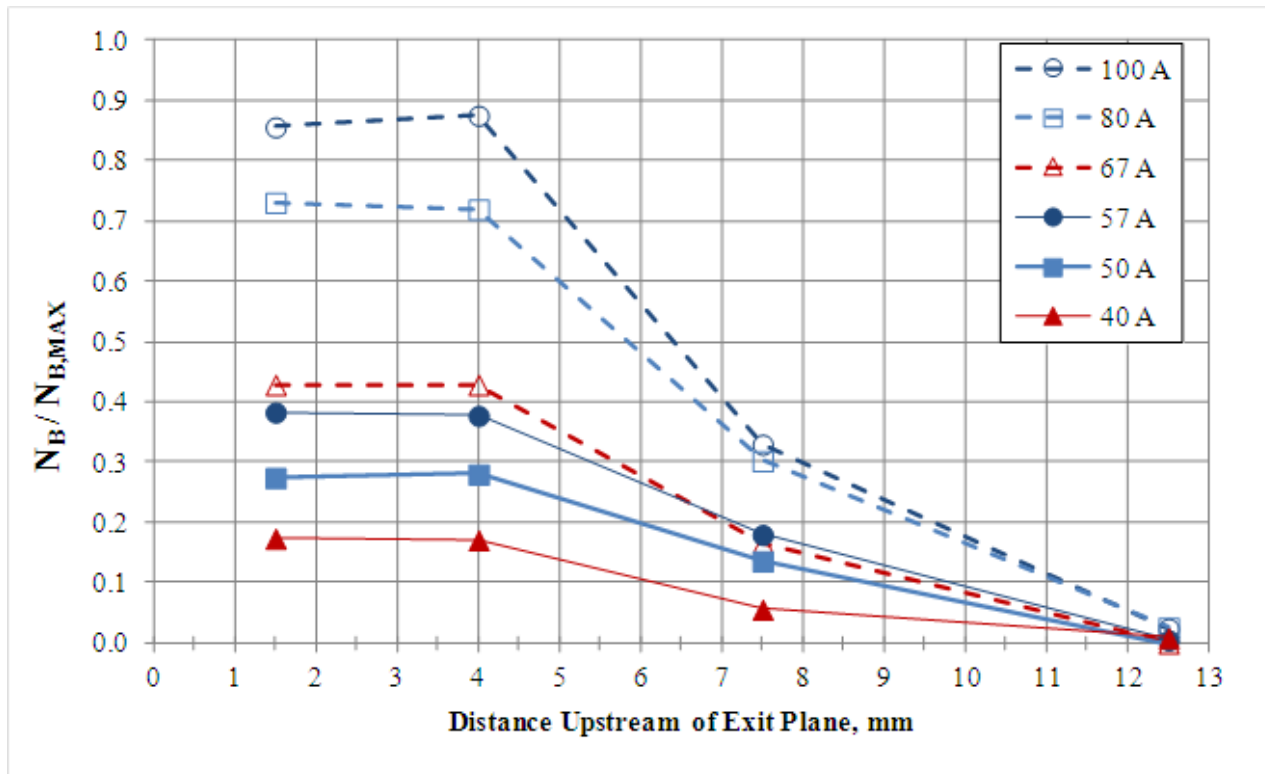
- N_B is at best a weak function of V_D
 - Implies erosion is function of J_D only
 - Inconsistent with expectations, experience, and theory
 - Extremely repeatable

B Emission in the NASA 457Mv2

- **Four optic probes collected light from the inner BN wall**
 - Each focused a few mm apart
 - UV-fused silica fibers and optics
- **One probe collected light from the outer BN wall**
 - A few mm upstream of the exit plane
 - UV-fused silica fibers and optics
- **NASA 457Mv2 operated over a range of powers**
 - See Soulas, AIAA-2012-3940
 - OES data taken at conditions with optimized magnetic field settings
 - B OES signals showed impact of off-nominal operation



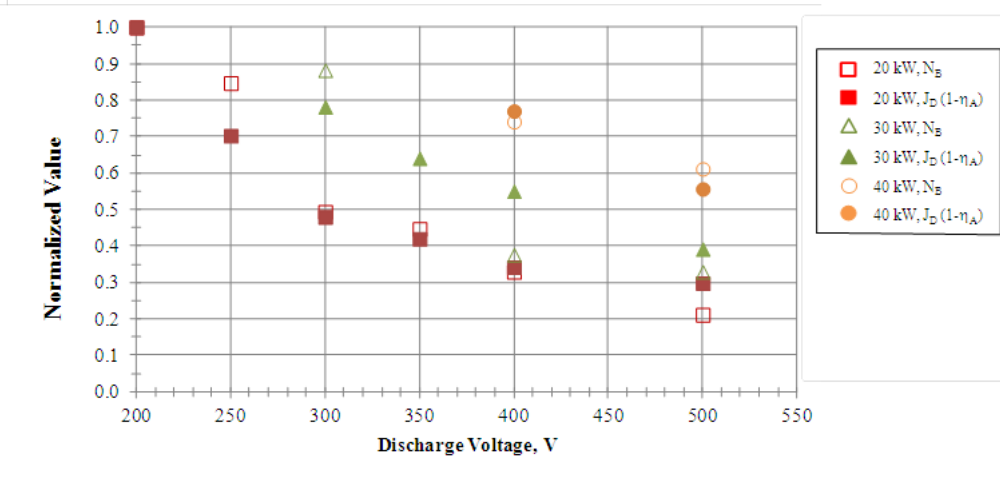
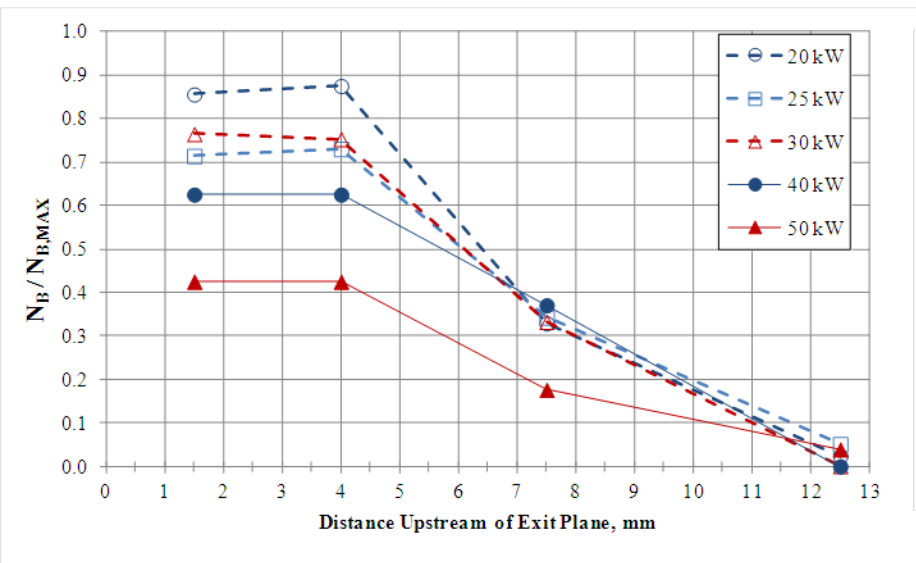
B Emission in the NASA 457Mv2



N_B values showed a clear variation with axial position

- Despite overlap in the bulk of the plasma—B emitting strongest near surfaces
- Increase with current for a given power level (25 kW shown)
- Marginal variation in pattern with current, some broadening with voltage

B Emission in the NASA 457Mv2



- N_B values decrease with power for fixed current ($J_D = 100$ A shown)
 - Suggests erosion zone is closer to the exit plane at lower voltages.
 - Suggests erosion will decrease at higher powers!
- N_B values shown to clearly decrease with V_D
 - Inconsistent with expectations, low-power experience, theory
 - Consistent with (but not the same trend as) NASA 300M N_B data
 - Values trend with $J_D(1-\eta_A)$, where η_A is the anode efficiency

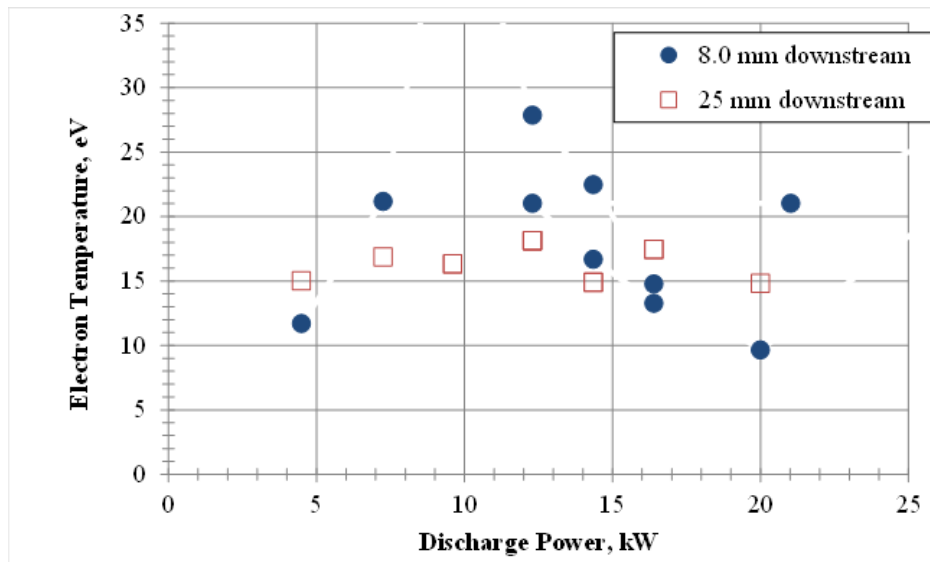
Summary of B OES Data

- **N_B data from the HiVHAC EM is consistent with expectations and several previous investigations**
- **N_B data from NASA 300M and NASA457Mv2 testing**
 - **Show a primary dependence on J_D instead of V_D**
 - **Suggest either**
 - **A significant difference in the correlation of erosion with thruster operating conditions in high-power thrusters OR**
 - **The inability of the OES technique to capture the erosion trend of high-power thrusters**
- **The most probable explanation is that the OES signals of both the B and Xe are being influenced by the higher-density plasmas of the higher-power thrusters in ways not taken into account.**

Near-Field Plasma Measurements

A collisional-radiative model was incorporated to evaluate the Xe plasma

- **Metastable states have long radiative lifetimes**
- **For $T_e < 10$, M-body collisions are important**
- **Using Chiu's approach for Xe I line ratios and tabulated values**
 - Rate coefficients calculated for different T_e
 - T_e determined from ratios of Xe I lines
 - Includes M-body collisional excitation
- **No useful data obtained from probes imaging walls, T_e too high**
- **Sporadic T_e measured in the plume**
 - Data agree with probe data
 - Very sensitive to OES noise



Chiu, Y. H., et al., "Passive Optical Diagnostic of Xe Propelled Hall Thrusters, Part 1: Emission Cross Sections

Summary and Conclusions

- The actinometrically corrected OES probing of erosion in the HiVHAc EM thruster yielded results
 - N_B values scale linearly with voltage
 - Integrated N_{Au} and N_{Ag} values agree with overall coupon erosion rates
- Results from testing with the NASA 300M and NASA 457Mv2 show unexpected trends in N_B
 - N_B values scale linearly with current
 - Suggests the technique may not be applicable as a high-power life predictor—OR it has identified a real, unexpected trend
- The OES technique still exhibited real-time B detection capabilities that will be of value in supporting high-power HET performance testing
- Optical plume measurements, including single frequency imaging may offer significant capabilities

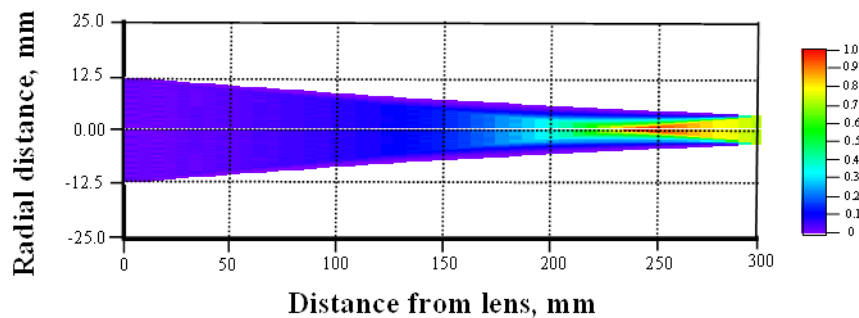


Back up

Fundamental Limitation of OES

A collisional-radiative model is needed to evaluate the Xe plasma

- **Metastable states have long radiative lifetimes**
- **For $T_e < 10$, M-body collisions are important**
- **Most collisional cross-sections are unknown**
- **Using Chiu's approach for Xe I line ratios and tabulated values**
 - **Rate coefficients calculated for different T_e**
 - **T_e determined from ratios of Xe I lines**
 - **Includes M-body collisional excitation**



NASA 457Mv2 Anode Efficiency

